Validation Analysis of the WAAS GIVE and UIVE Algorithms

Reza Ahmadi, Gregory S. Becker, Stephen R. Peck , Francois Choquette, and Thomas F. Gerard
Hughes Electronics
Anthony J. Mannucci, Byron A. Iijima, and Angelyn W. Moore
Jet Propulsion Laboratory, California Institute of Technology

BIOGRAPHIES

Dr. Reza Ahmadi is a staff engineer for Hughes Space and Communications Co. He has been responsible for the validation of the WAAS GIVE and UIVE algorithms. He has two years of experience at Hughes Space and Communications working on flight software for satellite attitude control systems and one year of experience in Hughes Aircraft Co. developing computer simulations of air-to-air mode performance for F-15 radar. He received a Ph.D. in Physics from UCLA in 1994.

Dr. Gregory S. Becker is a staff engineer at Hughes Aircraft Co. He has worked as an analyst on WAAS algorithm design and servo system design, since joining Hughes in 1996. He graduated from U.C. Berkeley with a Ph.D. in Control Theory in 1993, and performed post-doctoral research at INRIA-Roquencourt, France for two years.

Dr. Stephen R. Peck is a Senior Scientist for Hughes Aircraft Co. He is responsible for the algorithm development and validation for the WAAS reference stations and WAAS master stations. He has 11 years of experience with Hughes Aircraft in the navigation field and two years experience at JPL in the GPS network operations. He received his B.S. in Math, Physics from U.C. Davis in 1978, M.S. (79) and Ph.D. (84) from Harvard in Applied Mathematics (Control Theory).

Francois Choquette is a software engineer in the algorithm development group at Hughes on the WAAS project. Mr. Choquette has a BSEE from Concordia University in Montreal Quebec. He has been involved with aerospace real-time software applications since 1981.

Thomas F. Gerard is the lead software engineer for the GIVE algorithm at Hughes Aircraft Co. He has 14 years of experience in algorithm and software development of navigation and control systems. He received his M.S.E.E. from USC in 1994 and a B.S.S.E. from the University of Arizona in 1983.

Dr. Anthony J. Mannucci is a senior member of the technical staff in the GPS Networks and Ionospheric Systems Development Group at JPL. For the last 6 years, he has specialized in developing and applying ionospheric calibrations systems for deep space tracking and Earth science applications. Dr. Mannucci was lead engineer for the transfer of JPL's WAAS ionospheric software to Hughes Electronics. He holds a Ph.D. in physics from UC Berkeley.

Dr. Byron Iijima is a member of the GPS Networks and Ionospheric Systems Development Group at the Jet Propulsion Laboratory in Pasadena CA. For the last 8 years he has been developing technology for deep-space and GPS tracking applications. He is currently focused on GPS-based ionospheric maps, especially in real-time applications. He holds a Ph.D. in physics from MIT.

Dr. Angelyn W. Moore received her Ph.D. in Physics from the University of California, Riverside, in 1995. She began working at JPL in 1987, performing her undergraduate and graduate research in the area of ultrastable trapped-ion frequency standards. Since 1995 she has been a member of the GPS Networks and Ionospheric Systems Development Group, primarily developing near real-time systems for global ionospheric determination using a global network of GPS ground stations.

ABSTRACT

As a part of its "slow" error corrections, the Federal Aviation Administration's Wide-Area Augmentation System (WAAS) provides ionospheric vertical delays at geographically fixed Ionospheric Grid Points (IGPs). In addition to these vertical delays, WAAS's message type 26 contains Grid Ionospheric Vertical Errors (GIVEs) for the IGPs. GIVE values are required to bound the actual error with 99.9% confidence. Using the GIVE values a user can compute the User Ionospheric Vertical Errors (UIVEs) at each of his ionospheric pierce point locations. The UIVE scaled by an obliquity factor (F) is required to

53rd Annual ION Conference, July 1997

bound the users' ionospheric slant error at their pierce points with 99.9% confidence. In this paper we report the performance analysis of GIVE and UIVE algorithms using both simulated and real data. Several algorithm modification are considered. The 3 dimensional electron density of the ionosphere is simulated by the FAIM model. Phase one WAAS geometry (24 sites, 24 GPS satellites) is used in this analysis. The simulated users (162) are distributed across the CONUS. The analysis compares the user's slant ionosphere delay error to the UIVE value to determine if integrity requirements are met. Performance is analyzed, using a solar maximum scenario. Analysis shows that performance improvement is possible with the GIVE / UIVE modifications that still maintain the required integrity. Analysis of 26 days of real data, including one ionospheric storm, also demonstrates the 99.9% bounding integrity. Real data analysis demonstrates better performance, however, the ionosphere is currently near solar minimum as opposed to the solar maximum conditions that were simulated.

1. INTRODUCTION

The WAAS network provides, as part of its "slow" error correction, estimated Ionospheric Vertical Delays ($\hat{D}_{\mathrm{IGP}}$) at geographically defined ionospheric grid points (IGP), which make up the WAAS Grid. A single-frequency user, whose satellite line-of-sight (LOS) ionospheric pierce point (IPP) is contained in a cell within the WAAS Grid, can compute an estimate of the ionospheric delay using the broadcast vertical delays at the corresponding four IGPs, as shown in Figure 1. Using an analytic ionosphere model, which provides "truth" measurements of ionospheric delays, this paper analyzes several algorithms for computing conservative bounds on error of the broadcast value of $\hat{D}_{\mathrm{IGP}}$ and the user's computed vertical delay at an IPP.

Each IGP delay ($\hat{D}_{\mathrm{IGP}}$) is broadcast at 5 minute intervals along with a corresponding Grid Ionospheric Vertical Error (GIVE), which must provide a 99.9% confidence bound on the error between estimated IGP vertical delay ($\hat{D}_{\mathrm{IGP}}$) and the true vertical delay (D_{IGP}). The magnitude of GIVE at an IGP at a time (t_k) is derived from a statistical analysis of WAAS receiver station (WRS) measurements taken during the previous 5 minute interval and the values of $\hat{D}_{\mathrm{IGP}}$ broadcast at time ($t_k - 5$ minutes) for the nine IGPs defining the surrounding four cells, shown in Figure 2. The GIVE value should satisfy $\mathrm{GIVE}_{\mathrm{IGP}}(t_k) > \left|\hat{D}_{\mathrm{IGP}}(t_k) - D_{\mathrm{IGP}}(t)\right|$ for all $t_k \le t < (t_k + 5 \text{ minutes})$.

The user's ionospheric vertical error (UIVE) is the difference between the IPP vertical delay $\hat{D}_{\mathrm{IPP}}$ computed by a user based on $\hat{D}_{\mathrm{IGP}}$ and a "truth" vertical delay computed from the slant delay. Using the broadcast values of GIVE, the UIVE algorithm must provide a 99.9% confidence bound on the user's ionospheric vertical error (UIVE).

GIVE and UIVE must meet both accuracy and integrity requirements. The integrity requirement is that the UIVE, derived from the GIVE, must bound the user's ionospheric error with 99.9% confidence. The accuracy is a requirement derived from the overall system accuracy requirements:

- 7.6 meter 95% vertical and horizontal accuracy.
- Precision approach availability - must meet vertical protection limit (VPL) specification (19.2 meters).

To meet the latter requirement, the average ionosphere GIVE and UIVE values need to be about 1.5 to 2 meters for phase 1.

There is also a time-to-alarm requirement of 5.2 seconds in which the user must be protected from HMI (hazardously misleading information). A specific UIVE integrity monitoring algorithm exists in the safety processor to meet this requirement. However, due to message bandwidth required for alarms, it is very desirable to prevent HMI from ever being output from the GIVE algorithm in the first place. Thus, the GIVE is recalculated every 5 seconds as new ionosphere measurements are processed, which minimizes the chance for the broadcast GIVE values to underbound the user's error.

The RTCA MOPS (Minimum Operational Performance Standards) [3,4] specifies how a user computes an ionospheric vertical delay and UIVE bound at the user's IPP when all 4 surrounding IGP are monitored (have GIVE values). In phase 1, a significant number of IPPs will only have 3 of the 4 IGPs monitored. Our analysis will show that these users can also compute IPP delays and UIVE bounds from 3 monitored IGPs, thus increase availability. Several options for UIVE are presented in this paper.

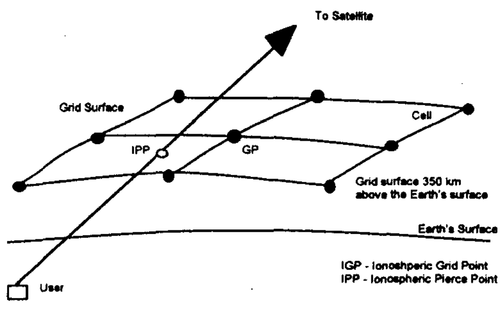


Figure 1. WAAS Grid geometry indicating IGP, IPP, and grid cell

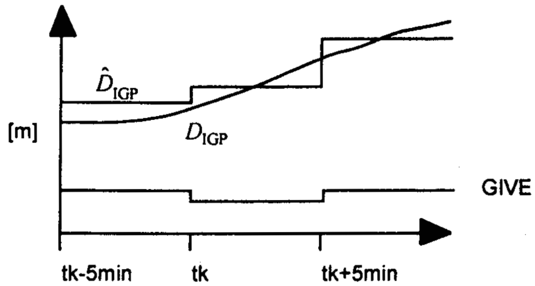


Figure 2. WAAS delay estimate and GIVE broadcast timing

2. DESCRIPTION OF SIMULATION

In this section we give a detailed description of the simulation that was performed to validate the integrity and performance requirements of the GIVE and UIVE algorithms.

Figure 3 contains a block diagram of the simulation code. The code simulates the computation of GIVE by WMS and UIVE by the users. In the next paragraphs we describe different components of the simulation code.

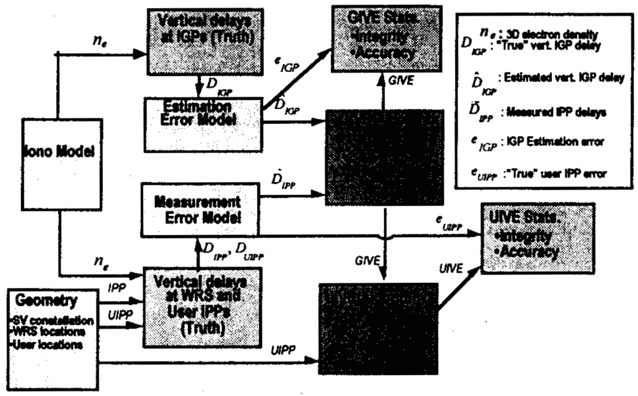


Figure 3. WAAS simulation code

2.1 SIMULATION GEOMETRY

WRS Network and Ionospheric Grid

The current network of 24 WAAS Reference Stations (WRS) used are shown in Figure 4. The stations are mainly located in the CONUS with the exception of those in Puerto Rico, Hawaii and Alaska.

The "truth" and estimated IGP vertical delays and GIVE values are computed on an imaginary grid located 350 km above the earth and covering North America: 10-55 degrees latitude and 225-315 East longitude equally spaced at 5 degree intervals. The resulting grid consists of 190 Ionospheric Grid Points (IGPs) defining 162 grid cells.

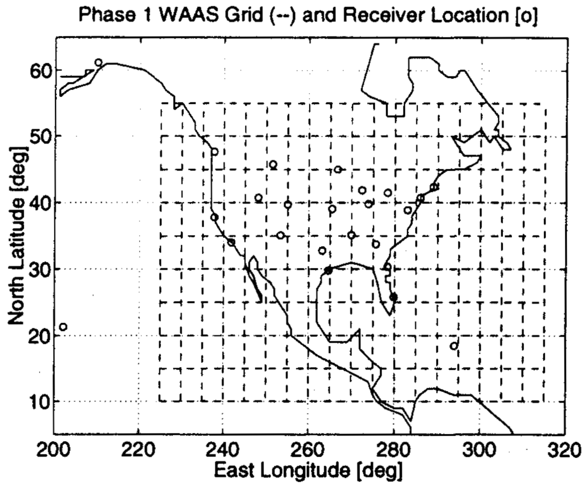


Figure 4. WAAS Phase I geometry

Satellite Constellation

The satellite constellation used consists of the 24 GPS satellites. The position of these satellites in ECEF coordinate system are propagated in time using the almanac data at a reference epoch. The almanac data used consists of the six Keplerian elements (i.e. mean anomaly, argument of Perigee, eccentricity, semimajor axis, inclination and longitude of the ascending node) and the time derivative of the inclination. The computation of the position of the satellites as a function of time (with respect to the reference epoch) is standard.

2.2 Ionospheric "Truth" Model

The Fully Analytical Ionosphere Model (FAIM) [1], provides simulated data for high ionospheric conditions. The FAIM model provides electron density as a function of the following inputs:

- Geodetic coordinates (latitude, longitude, altitude)
- Universal Time (UT)
- Day number (a number between 1 and 365, Jan 1[st] = day 1)
- Sun Spot Number (SSN)

The slant delay due to the ionosphere along a given LOS can be obtained by numerical integration of the electron density. For L1 frequency the delay in meters is given by the following equation:

$$D = \frac{1}{2f_{L_1}^2}\int_{LOS} f_p^2\,ds = \frac{e^2}{2f_{L_1}^2\varepsilon_o m_e}\int_{LOS} n_e(s)\,ds$$

where:

f_{L_1} = L_1 frequency

n_e = Electron Number Density

f_p = Electron Plasma Frequency

m_e = Mass of the Electron

e = Charge of the Electron

ε_o = Permitivity of Free Space

Inserting the numerical values for e and m_e, the delay [in meters] in terms of the electron number density [in meters^{-3}] is

$$D\,[\mathrm{m}] = 1.624538252 \times 10^{-17} \int_{\mathrm{LOS}} n_e(s)ds$$

The "true" vertical delays are computed at each of the IGPs, and the "true" slant delays from a reference station or user to a satellite are computed by integrating the electron density from a reference station's position or user's position along the LOS of the satellites in view.

The example in Figure 5 shows the L1 vertical delay at 25 degrees latitude and 20 degrees longitude as a function of UT and SSN. Figure 6 shows the L1 vertical delay over the WAAS grid on Day 100 with SSN = 100 at both, UT 18 Vs UT 8.

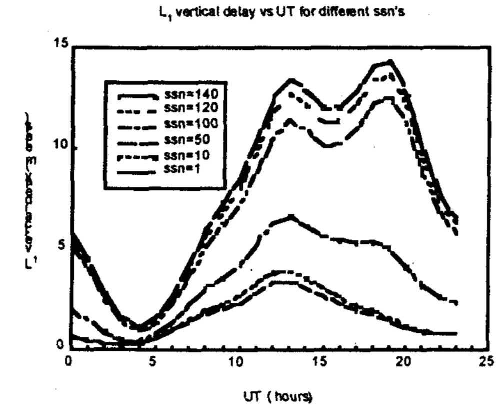


Figure 5. L1 Vertical Delay as a function of UT and SSN

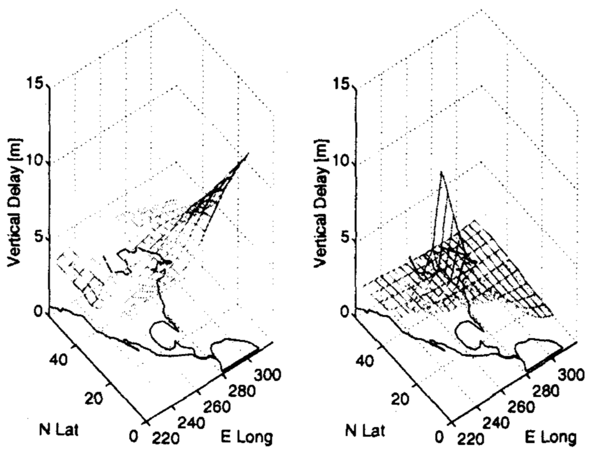


Figure 6. L1 Vertical Delay over CONUS UT 18 vs. 8

2.3 Error Modeling

IGP Vertical Delay Estimation Error

The WMS estimates the vertical delay at each IGP using a Kalman Filter with a 5 minute update rate. The estimation error, the difference between the "true" IGP vertical delays and the IGP delays estimated by the WMS, is modeled as a first-order Gauss-Markov process characterized by a standard deviation (σ) of 0.3 meters and correlation time (τ) of 120 minutes. This model is based on results from JPL real-time WAAS ionospheric software (WIS). Some of these results were presented in reference[2].

Measurement Error

The receiver/satellite measurement error is the difference between the "true" slant delay and the slant delay measured by the WRSs. The three main contributors to the measurement error are: 1) the receiver error, 2) the L1-L2 inter-frequency bias error, and 3) the multipath error. These errors are also assumed to be first order Gauss-Markov processes. Analysis of real data shows that the multipath error can have a rms. of as large as 1 meter for low elevation angles. However, as the receiver acquires and continues to track a satellite, the continuous carrier phase leveling quickly decreases the impact of the multipath error as the elevation angle increases towards is maximum level. As an approximation of real data, the following elevation angle dependent value of multipath variance is used:

$$\sigma_{multi} = \sigma_{floor} + \frac{\sigma_{rise/fall}}{\tan(\theta^*)}$$

where: θ^* = elevation angle for rising satellites, max. elevation angle for setting satellites.

Error Type	σ (in meters)	τ (in seconds)
Phase Receiver Error	0.01	30
L1-L2 inter-frequency bias	0.1	86,400 (1 day)
Multipath	σ_{floor} = 0.05 $\sigma_{rise/fall}$ = 0.03 $\sigma_{rise/fall}$ =0	300

Table 1. Measurement Errors

This model is based on data collected from the Novatel receiver planned for use in the WAAS system. The output of the data editor (leveled carrier phase) was analyzed to obtain the model in Table 1.

2.4 GIVE COMPUTATION

The GIVE algorithm calculates a conservative bound on the error between the true vertical delay at an IGP (D_{IGP}) and its broadcast estimate ($\hat{D}_{IGP}$) using slant delay measurements from valid WRS receiver/satellite pairs. At any time t , a WRS receiver/satellite pair is considered valid if the elevation angle of the satellite is greater than 5 degrees and the Ionospheric Pierce Point (IPP) is within a cell of the WAAS Grid. The measured vertical delay ($D_{IPP}(t)$) at an IPP is computed by scaling the measured receiver/satellite slant delay by an elevation angle dependent obliquity factor.

$$F(\theta) = \frac{1}{\sqrt{1-\left(\frac{R_e \cos\theta}{R_e + h_m}\right)^2}}$$

where θ is the elevation angle, R_e is the Earth's radius, and h_m is the grid height (350 km). An estimate of the vertical delay ($\hat{D}_{IPP}(t)$) at a WRS IPP is computed from the current $\hat{D}_{IGP_i}$ at the four cornerpost grid nodes of the corresponding cell. The WMS updates the values of $\hat{D}_{IGP}$ every 5 minutes. The computed IPP vertical error is defined to be $e_{IPP}(t) = \hat{D}_{IPP}(t) - D_{IPP}(t)$. Over each 5 minute period, the vertical errors for each IPP trace are computed at 5 second intervals for each of the four cells surrounding an IGP (see Figure 8). Nominally, there are 60 points in a trace, but some traces may contain fewer points; for example, they might just be acquired during the sample window, or may just be meeting the minimum LOS elevation angle of 5 degrees.

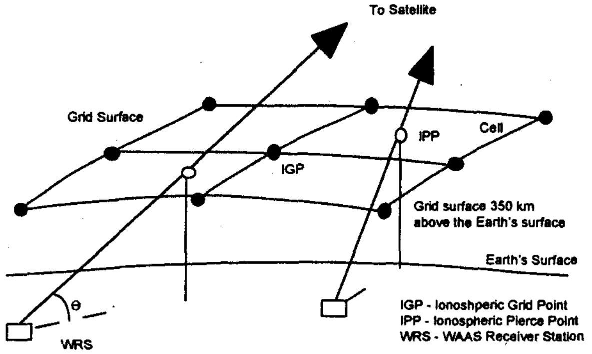


Figure 7. WAAS GIVE Computation Geometry.

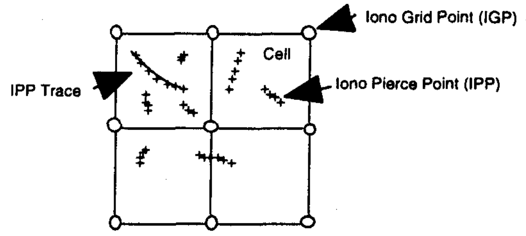


Figure 8. IPP trace patterns over sample window.

A statistical analysis is performed on this data and a value for GIVE is assigned to the IGP. To validate the integrity of the algorithm, the GIVE value is compared to the actual vertical delay estimate error over the following 5 minute interval to obtain the GIVE bound:

$$B_{IGP} = \frac{\left|D_{IGP}(t) - \hat{D}_{IGP}(t_k)\right|}{\text{GIVE}(t_k)} \quad \text{for all} \quad t_k \le t < (t_k + 5 \text{ minutes})$$

The GIVE performance requirement requires that B_{IGP} be less than 1 for 99.9% of the time.

Several different methods and variations were considered for computing GIVE. The original baseline was based on a GIVE algorithm developed by MITRE [3,4]. Due to the additional pre-processing in our current design, the resulting GIVE values were not always bounding the ionospheric error. Many modifications were studied with both the simulation and real-data tools to arrive at the selected GIVE algorithm that meets integrity requirements and provides sufficient accuracy performance. The selected WAAS GIVE algorithm obtains a 99.9% confidence bound of all e_{IPP} in each adjoining cell based on the RMS of the e_{IPP} and χ^2 statistics. The GIVE values are derived from the bounds of adjoining cells, with the requirement that e_{IPP} exist in at least 3 of the 4 cells. This method has been denoted "3rd Max. Cell RMS".

2.5 UIVE COMPUTATION

To test the integrity of the User Ionospheric Vertical Errors (UIVEs), a fictitious user is placed in the center of each of the 162 grid cells at an altitude of 0 meters. For a valid user's IPP, the user's estimated vertical delay $\hat{D}_{UIPP}$ is computed from the four cornerpost $\hat{D}_{IGP_i}$'s of the IPP's bounding cell, and similarly the estimate of the vertical error $\widehat{\text{UIVE}}_{UIPP}$ is computed from the corresponding four GIVE values. The true slant delay is computed and scaled by the obliquity factor to obtain the true calculated vertical delay (D_{UIPP}), and a value of the true UIVE is obtained $\text{UIVE}_{UIPP} = \left|D_{UIPP} - \hat{D}_{UIPP}\right|$. To validate the integrity of the algorithm, the UIVE value is compared to the true UIVE to get the UIVE Bound,

$$B_{\mathrm{UIPP}} = \frac{\mathrm{UIVE}_{\mathrm{UIPP}}}{\hat{\mathrm{UIVE}}_{\mathrm{UIPP}}}$$

Two basic approaches to UIVE are considered:

1) UIVE is computed from a maximum function operating on the surrounding GIVE values. Results from two variations are shown:
1a) Set UIVE to the 3rd highest surrounding GIVE value when all 4 surrounding IGP are monitored (denoted "3rd Max." in Table 2). Note that the user calculates his ionospheric delay from $\hat{D}_{\mathrm{IGP}}$ as specified in the RTCA MOPS document [5,6].

1b) Requires 3 or 4 monitored IGP and the user's IPP to be within the convex hull defined by the monitored IGP (i.e. the IPP must be in the triangle defined by the monitored IGP when only three are monitored). Note that if all IGP are monitored, the user calculates his ionospheric delay from $\hat{D}_{\mathrm{IGP}}$ as specified in the RTCA MOPS document. If only three IGP are monitored, the user calculates the vertical ionospheric delay from the unique linear weighting from the IGP to his IPP applied to the monitored $\hat{D}_{\mathrm{IGP}}$ (denoted "3rd Max. Tri" in Table 2).

2) UIVE is computed by interpolation from the surrounding GIVE values:

$$\mathrm{UIVE} = \sum_{i=1:4} W_i(x_{pp}, y_{pp})\mathrm{GIVE}_i$$

as specified in [4]. Results from three variations are shown:

2a) Standard MOPS as defined in RTCA MOPS (mod 8) which requires all 4 surrounding IGP to be monitored (denoted "MOPS" in Table 2).

2b) Requires 3 or 4 monitored IGP and the user's IPP to be within the convex hull defined by the monitored IGP (i.e. the IPP must be in the triangle defined by the monitored IGP when only three are monitored.). This method is identical to 2a when all 4 IGP are monitored. When 3 IGP are monitored, the user computes the UIVE and ionospheric delay linearly from the IGP GIVE values and $\hat{D}_{\mathrm{IGP}}$ respectively. This method is denoted "MOPS Tri" in Table 2.

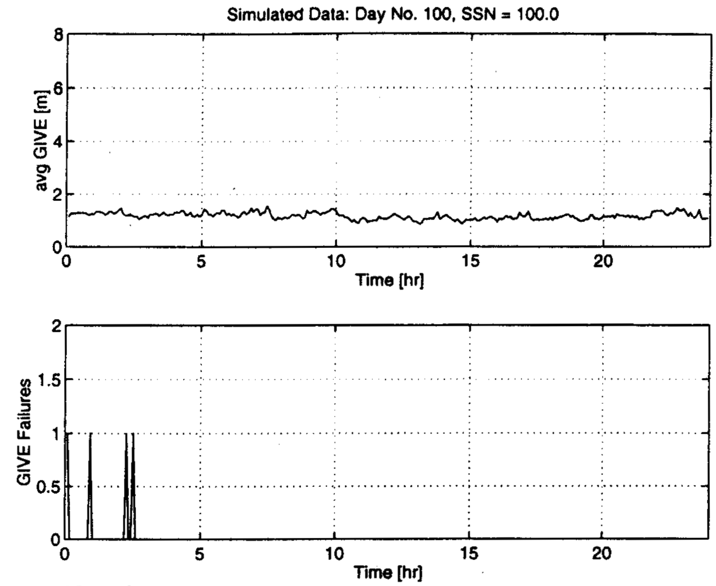
2c) Requires 3 or 4 monitored IGP (denoted "3 Pt MOPS" in Table 2). If 3 IGPs are monitored, the user computes his ionospheric delay linearly from the monitored $\hat{D}_{\mathrm{IGP}}$, but the UIVE is computed using a non-negative weighted combination of the GIVE values given by:

$$\mathbf{UIVE} = \frac{\sum_{i=1:3} \mathbf{max}\left(W_i(x_{pp}, y_{pp}), 0\right)\mathbf{GIVE}_i}{\sum_{i=1:3} \mathbf{max}\left(W_i(x_{pp}, y_{pp}), 0\right)},$$

where the W_i are the linear weights of the monitored IGP. Note, this is equivalent to 2b when the IPP is within the convex hull of the monitored IGP.
Geometry studies have shown that 2b) yields 15% more ionospheric monitoring for the CONUS user and 1b), 2c) provide approximately 30% more ionospheric monitoring when compared with 1a) or 2a).

3. SIMULATION RESULTS

In this section we present the simulation results of the current GIVE design (3rd Max. Cell RMS) and candidate UIVE options. Note that integrity is met for all UIVE options. Our preferred option is "3 Pt MOPS" because of the increased monitoring, and thus availability, for the user. The mean value of B_{UIPP} is shown as a sanity check on the integrity of the UIVE. For a zero-mean Gaussian distribution of errors, the 99.9% distribution limit is approximately 4 times the average absolute value of the distribution. Thus, we would expect the mean of B_{UIPP} to be less than 0.25 for a UIVE that bounds with 99.9% confidence.



Total IGP points monitored: 16547
Mean GIVE: 1.17 meters
% Fail B_{IGP} : 0.49
Mean B_{IGP} : 0.25
Max. B_{IGP} : 1.99

Figure 9. GIVE Performance Summary based on "3rd Max. Cell RMS" method.

UIVE Method	Mean UIVE (meters)	% Fail B_{UIPP}	Mean B_{UIPP}	Max. B_{UIPP}
3rd Max.	1.21	0.03	0.18	1.39
3rd Max. Tri	1.26	0.06	0.18	1.75
MOPS	1.05	0.05	0.19	2.61
MOPS Tri	1.09	0.06	0.19	2.61
3 Pt MOPS	1.13	0.10	0.20	2.61

Table 2. UIVE Performance Summary based on "3rd MAX. Cell RMS" GIVE values (Simulation)

4. REAL DATA ANALYSIS

Twenty six days of real GPS data were generated and analyzed during April and May 97. The 99.9% GIVE bound requirement was met on all 26 days using some post-processing of the intermediate results. Final results of a typical ionospheric day (May 21, 1997) and of one ionospheric storm day (April 22, 1997) are presented.

4.1 DATA SOURCES

The real data sources used were from the Satloc Corporation and the International GPS Service for geodynamics (IGS) networks.

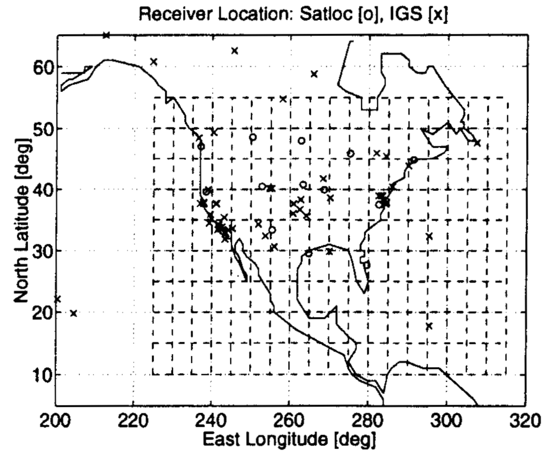


Figure 10. Satloc and IGS Receiver Location

The Satloc network is a private network that comprises 14 receivers spread fairly evenly across CONUS (See reference [2] for network description). This network was sufficient to cover the Phase 1 WAAS grid as shown in Figure 10 above. Not all 190 WAAS grid points could be monitored at all times due to receiver location and satellite availability. The analysis only includes the WAAS grid cells that met the minimum monitoring requirements as would be expected in the real WAAS system. The Satloc data used in this analysis is processed by JPL to produce leveled carrier phase measurements every five seconds and a Kalman filtered WAAS delay at every five minute interval.

The IGS network is a large (200+ receivers) worldwide GPS network with about 50 receivers located within CONUS. The IGS network acts as a truth reference to verify that the candidate GIVE algorithm meets the 99.9% bound requirement. JPL post-processes this data daily to precisely calculate receiver and satellite biases and improve accuracy.

4.2 TEST METHOD

At each five minute period, each Satloc receiver produces up to 60 samples of five second data. A minimum of 10 samples per WAAS cell is needed to produce valid GIVE statistics. Depending on Satloc receiver location and satellite geometry, we discard data from satellites with elevation angles less than 5 degrees.

This data is collected and differenced against the Kalman filtered WAAS grid to produce error samples that are statistically analyzed. From the cell statistics, error bounds are calculated at each WAAS grid cell. All 190 monitored WAAS grid points are assigned a GIVE value based on the surrounding cell error bounds. Some will be assigned the "Not monitored" value if data is insufficient. The calculated GIVE value is rounded up to the next GIVE index value as described in Table 16 of [3].

A comparison of these results is made to the IGS network. The IGS network produces data at the same five minute periods as the Satloc WAAS grid. On average, 280 truth reference user points are available at each five minute interval, roughly 65% of which fall within the monitored cells of the Satloc WAAS grid. Typically, a total 40-50,000 monitored truth reference measurements are available per day to validate the computed GIVE values.

Each IGS slant measurement is converted to a vertical ionospheric delay by dividing with the aforementioned obliquity factor. The IGS pierce point location is used to compute a Satloc vertical delay through MOPS interpolation. The IGS vertical delay is then subtracted from the Satloc vertical delay. We call this user error the true User Ionospheric Vertical Error or "true UIVE". The GIVE values from the WAAS Satloc grid produce the pierce point UIVE using the interpolation options discussed in section 2.3. The IGS true UIVE is then compared with the Satloc UIVE. If the IGS true UIVE exceeds the Satloc UIVE, then GIVE has failed to bound the user's error at that point. 50 such failures on a truth sample size of 50,000 are allowed to meet the minimum 99.9% integrity requirement.

4.3 RESULTS

With the candidate GIVE algorithm chosen (3rd MAX. Cell RMS) initial results failed to meet the 99.9% integrity requirement. Our initial results were between 99.5% and 99.9% integrity. Since the GIVE algorithm was mathematically sound we closely analyzed the IGS truth data.

Several methods were applied to filter errors in the IGS truth data.

1) The Satloc data uses 2 Ionospheric thin shells heights at 450 and 550 kilometers for the pierce point location and obliquity factor calculations respectively. We adjusted our processing and the IGS Ionospheric model accordingly and further lowered GIVE bound failures.
2) Occasionally, a few IGS receivers produced radically different ionospheric delays (for a period of time) compared to Satloc delays at one point during the day and for the rest of that day. We suspect this effect is due to L1-L2 bias stability problems. The problem goes away the next day because new receiver and satellite biases are calculated and included in the IGS truth data. The receivers that exhibited this problem were discarded for that day's analysis.
3) (Not used in analysis shown) The remaining failures were usually borderline and we had to determine if these failures were real GIVE failures or other IGS problems. We looked at all the co-located IGS receivers that received data from the same satellite at the same time period as the failed data point. If all other IGS receivers looking at the same portion of the sky were in close agreement and substantially different from the receiver in question, that receiver's data point is discarded.

The first 2 methods allowed us to achieve integrities as high as 99.99% on some days therefore validating our GIVE algorithm with confidence. The third method was used to evaluate how many of the "integrity failures" were due to ionosphere errors greater than UIVE, and how many were due to anomalies in the IGS truth data used.

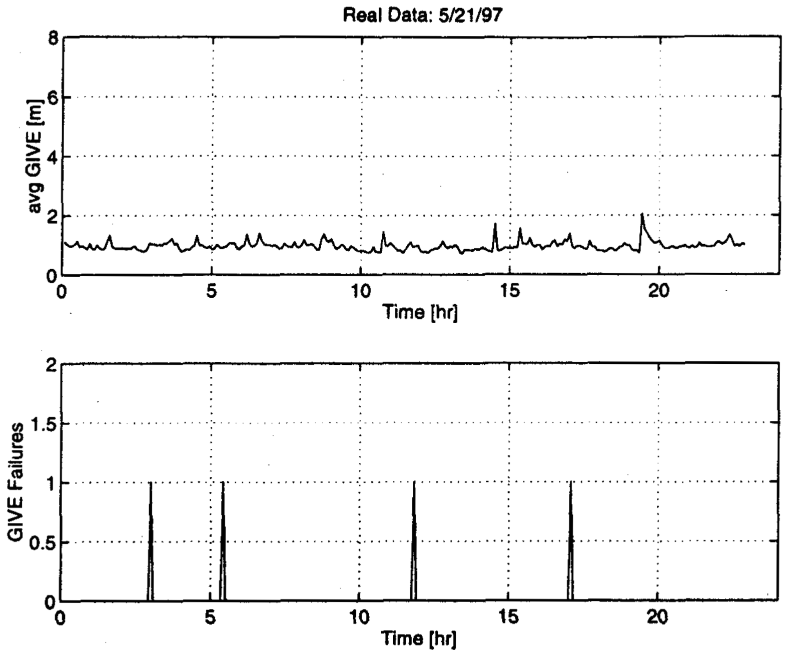
Figures 11 and 12 show the GIVE performance in a normal and storm day respectively. They show that the GIVE meets the integrity requirements in both days. The accuracy requirement is met except 2 hours in the storm day. The UIVE performance for these two days as shown in table 3 and table 4 indicate that all three UIVE options meet the performance requirements.

UIVE Method	Mean UIVE (meters)	% Fail B_{UIPP}	Mean B_{UIPP}	Max. B_{UIPP}
MOPS	0.95	0.0086	0.15	0.14
MOPS Tri	1.10	0.0073	0.14	0.99
3 Pt MOPS	1.18	0.0086	1.18	1.08

Table 3. Day 5/21/97 - UIVE Performance Summary based on "3rd Max. Cell RMS" GIVE values

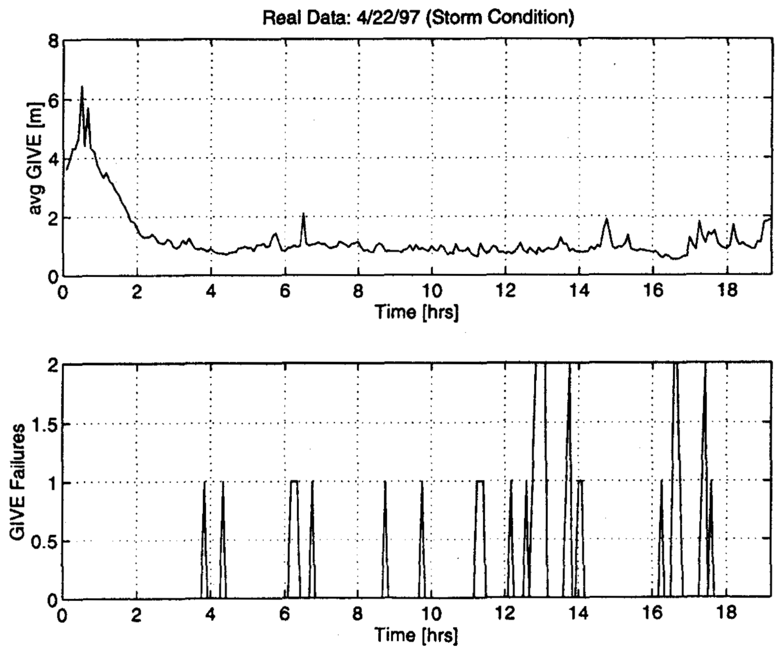
UIVE Method	Mean UIVE (meters)	% Fail B_{UIPP}	Mean B_{UIPP}	Max. B_{UIPP}
MOPS	1.15	0.1062	0.16	1.48
MOPS Tri	1.15	0.1063	0.15	1.48
3 Pt MOPS	1.17	0.1062	0.15	1.48

Table 4. Day 4/22/97 - UIVE Performance Summary based on "3rd Max. Cell RMS" GIVE values



Total IGS truth reference points : 73271
Total truth ref. pts not monitored : 27042
Total GIVE failures : 4
Final GIVE integrity: 99.99

Figure 11. Real data plot of GIVE average and GIVE bound (B_{IGP}) meeting 99.9% bound requirement (Normal day, 5/21/97)



Total truth ref. pts : 67749
Total truth ref. pts not monitored : 24607
Total GIVE failures : 45
Final GIVE integrity: 99.90

Figure 12. Real data plot of GIVE average and GIVE bound (B_{IGP}) meeting 99.9% bound requirement (Storm day, 4/22/97)

UIVE Method	Mean UIVE (meters)	% Fail B_{UIPP}	Mean B_{UIPP}	Max. B_{UIPP}
MOPS	1.0346	0.073	0.15	2.60
MOPS Tri	1.0561	0.071	0.15	2.60
3 Pt MOPS	1.0798	0.068	0.15	2.60

Table 5. 26 Day Summary of UIVE Performance based on "3rd Max. Cell RMS" GIVE values

5. CONCLUSIONS

The WAAS GIVE algorithm has been developed with the aid of validation analysis to ensure that integrity and accuracy requirements have been met. The analysis to date includes real data analysis of 26 days including one ionosphere storm, and a simulation based on the FAIM 3-D ionosphere model of solar maximum conditions, and error models developed from real-data analysis. Variations of the user's UIVE algorithm were analyzed to increase the availability of monitored computed ionospheric delays.

The GIVE method selected ("3rd max. RMS cell") meets the integrity requirement of bounding the ionosphere error with 99.9% confidence both in the simulated solar maximum conditions, and the current ionospheric conditions (nominal and storm). The accuracy performance is sufficient for all WAAS phases, with the exception of storm conditions. For two hours, the GIVE values were high enough to reduce the availability of precision approach on April 22, 1997. Both accuracy and integrity showed little degradation when UIVE modifications requiring only 3 of 4 surrounding grid points to be monitored. With both simulated and real data, this UIVE algorithm would provide a 30% increase in the user's ionospheric delay availability, and thus have a significant impact on the precision approach availability. Possible modifications to the RTCA MOPS UIVE will be pursued to take advantage of this increased availability.

Future work will focus in two areas. First, more real data analysis is needed to gather sufficient evidence to modify the UIVE that the user will implement. Second, more analysis of storm data will be used to determine if modifications to the GIVE algorithm will improve accuracy, while maintaining integrity during a storm. At this point, the current GIVE will be implemented in phase I, and modifications would be implemented in future WAAS phases.

ACKNOWLEDGMENTS

This work was performed by Hughes Electronics and JPL under contract with FAA. Real time data was provided by SATLOC Corporation. The authors would like to thank Juan Ceva for stimulating discussions.

REFERENCES

[1] Anderson, D.N., J.M. Forbes, and M. Codrescu, A fully analytical, Low-and Middle-Latitude Ionospheric Model, J. Geophys. Res., Vol. 94, p. 1520, 1989

[2] Bertiger, W. I., Y. E. Bar-Server, B.J. Haines, B. A. Iijima, S. M. Lichten, U. J. Lindqwister, A. J. Mannucci, R. J. Muellerschoed, T. N. Munson, A. W. Moore, L. J. Romans, B. D. Wilson, S. C. Wu, T. P. Yunck, G. [3] Piesinger, and M. Whitehead, A Prototype Real-Time Wide Area Differential GPS System, Proceedings of ION National Technical Meeting, Santa Monica, CA, January 1997.

[3] Conker, R., M. B. El-Arini, T. Albertson, J. Klobuchar, P. Doherty, Development of Real-Time Algorithms to Estimate the Ionospheric Error Bounds for WAAS, Proceedings of the ION GPS-95, Palm Springs, CA, September, 1995, pp. 1247-1258.

[4] RTCA (1996), Minimum operational performance standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, Technical report, RTCA.

[5] RTCA (1997), Minimum operational performance standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, Technical report, RTCA (mod 8).

[6] Mannucci, A. J., B. A. Iijima, B. D. Wilson, S. R. Peck, R. Ahmadi, M. Hagen, "Wide Area Ionospheric Delay Corrections Under Ionospheric Storm Conditions", Proceedings of ION National Technical Meeting, Santa Monica, CA, January 1997.